REFRACTIVE BOUNDARY ELEMENTS, DEVICES, AND MATERIALS

TECHNICAL FIELD

The present invention relates to optical elements, methods, or materials for refraction.

BACKGROUND

One common type of refraction is the bending of the path of a lightwave as it crosses a boundary between two media. In conventional optics, Snell's law gives the relationship between the angles of incidence and refraction for wave crossing the boundary:

$$n_1 \sin(\Theta_1) = n_2 \sin(\Theta_2).$$

This relationship is shown in Figure 1, where a ray 100 in a first medium 101 arrives at a boundary 102 at an angle Θ_1, as referenced to the normal 104. As the ray 100 crosses the boundary 102, the ray 100 is bent so that it continues propagating as a refracted ray 106 at an angle Θ_2.

While this relatively simple ray optics presentation of refraction is widely accepted, a more thorough examination of refraction involves consideration of propagation of electromagnetic waves and considerations of energy reflected at a boundary. Figure 2A represents this diagrammatically with an incident wave 108 crossing a boundary 110. A portion of the energy is reflected as represented by the wave 112 and a portion of the energy propagates as a transmitted wave 114. As represented by the spacing between the waves, the wavelength of the transmitted wave 114 is shorter than that of the incident wave 112, indicating that the refractive index n_2 experienced by the transmitted wave 114 is higher than the refractive index n_1 experienced by the incident wave 108.

As indicated by the figures and by Snell's law, a lightwave traveling from a lower index of refraction to a higher index of refraction will be bent toward the normal at an angle determined by the relative indices of refraction. For this system, in a conventional analysis, the range of refracted angles relative to the normal is typically confined to a range from 0 degrees to a maximum angle determined by an angle of total reflection. Additionally, the amount of light energy reflected at the boundary is a function of the relative indices of refraction of the two materials.

More recently, it has been shown that under certain limited conditions, rays traveling across a boundary may be refracted on the same side of the normal as the incident ray in a phenomenon called "negative refraction." Some background on the developments can be found in Pendry, "Negative Refraction Makes a Perfect Lens," Physical Review Letters, Number 18, October 30, 2000, 3966-3969; Shelby, Smith, and Schultz, "Experimental Verification of a Negative Index of Refraction," Science, Volume 292, April 6 2001, 77-79; Houck, Brock, and Chuang, "Experimental Observations of a Left-Handed Material That Obeys Snell's Law," Physical Review Letters, Number 13, April 4, 2003, 137401-(1-4); each of which is incorporated herein by reference. With particular reference to negative refraction, Zhang, Fluegel and Mascarenhas have demonstrated this effect at a boundary between two pieces of YVO_4 crystal, where the pieces of crystal are rotated such that the ordinary axis of the first piece is parallel to the extraordinary axis of the second piece. This demonstration was presented in Zhang, Fluegel and Mascarenhas, "Total Negative Refraction in Real Crystals for Ballistic Electrons and Light," Physical Review Letters, Number 15, October 10, 2003, 157404-(1-4), which is incorporated herein by reference. Figure 2B shows the interface, the relative axes and the nomenclature used in the descriptions herein for the case of positive refraction. Figure 2C shows the same aspects for negative refraction.

The YVO_4 crystal treated by Zhang, et al., is an example of an anisotropic crystal whose dielectric permittivity is defined by the matrix,

$$\begin{pmatrix} \varepsilon_o & 0 & 0 \\ 0 & \varepsilon_e & 0 \\ 0 & 0 & \varepsilon_z \end{pmatrix}$$

and where ε_o, ε_e, and ε_z are not all the same. In general, the refractive index n of a medium is related to the dielectric permittivity ε as,

$$n = c\sqrt{\mu\varepsilon},$$

where μ is the magnetic permeability of the medium.

SUMMARY

In an optical element having materials of differing properties, the material properties may define an interface or other transition that may refract light traveling through the materials. In one aspect, the element may include two or more materials that define one or more boundaries. The material properties and/or orientation may be selected to establish refraction at the boundary. In one aspect, the material properties are refractive indices or dielectric constants. The properties may be selected so that refraction at the boundary is substantially reflectionless.

In one approach, materials are selected to define a boundary. The materials are selected with refractive indices that are related according to the geometric means of their constituents. In one approach, the constituents are normal and extraordinary indices of refraction. In one approach, at least one of the materials is an anisotropic material. In one approach two or more of the materials are anisotropic. In one approach one or more of the materials is anisotropic according to its index of refraction. Where one or more of the materials is anisotropic, the anisotropic materials are oriented such that the following boundary conditions are satisfied by a wave incident on the boundary:

$$\hat{z} \cdot \vec{H}_1 = \hat{z} \cdot \vec{H}_2$$
$$\hat{y} \cdot \vec{E}_1 = \hat{y} \cdot \vec{E}_2$$
$$\hat{y} \cdot \vec{k}_1 = \hat{y} \cdot \vec{k}_2$$

In one approach, the materials have dielectric constants and orientations that satisfy the relationship:

$$\beta_1 \varepsilon_1{}^2 = \beta_2 \varepsilon_2{}^2$$

$$\sqrt{\beta_1} \cos^2 \phi_1 + \frac{1}{\sqrt{\beta_1}} \sin^2 \phi_1 = \sqrt{\beta_2} \cos^2 \phi_2 + \frac{1}{\sqrt{\beta_2}} \sin^2 \phi_2$$

In addition to the foregoing, various other method and/or system aspects are set forth and described in the text (e.g., claims and/or detailed description) and/or drawings of the present application.

The foregoing is a summary and thus contains, by necessity; simplifications, generalizations and omissions of detail; consequently, those skilled in the art will appreciate that the summary is illustrative only and is NOT intended to be in any way limiting. Other aspects, inventive features, and advantages of the devices and/or processes described herein, as defined solely by the claims, will become apparent in the non-limiting detailed description set forth herein.

BRIEF DESCRIPTION OF THE FIGURES

Figure 1 is a ray diagram showing propagation of a light ray across a boundary between two media.

Figure 2A is a propagation diagram showing propagation and reflection of a wave at a boundary.

Figure 2B is a diagram showing a boundary and nomenclature associated with beam propagation.

Figure 2C is a diagram showing a boundary and nomenclature associated with beam propagation for negative refraction.

Figure 3 is a representation of a wave propagating across the boundary between two different media having equivalent geometric means of their ordinary and extraordinary indices of refraction.

Figure 4 is a representation of a three layer structure with a ray propagating through two interfaces between the layers.

Figure 5 is a representation of a structure having five layers, each having a respective index of refraction.

Figure 6 is a side view of a stack of three materials having non-uniform thicknesses.

Figure 7 is a side view of a stack of three materials, where the central material has a graded index of refraction.

Figure 8 is a diagrammatic representation of a pair of materials, where one of the materials is a dynamically controllable material.

Figure 9 is a diagrammatic representation of a stack of materials where the central material is a dynamically controllable material.

Figure 10 is a diagrammatic representation of a circulator and waveguide.

Figure 11 is a representation of a manmade material having selected electromagnetic properties.

DETAILED DESCRIPTION

As shown in Figure 3, a first ray 300 travels through a first medium 302 with a first index of refraction n_1 at an angle Θ_1 relative to a normal 306. The index of refraction n_1 that ray 300 sees depends on the ordinary and extraordinary indices of refraction of the medium, and also depends on the angle the ray 300 makes with the ordinary axis $\hat{o}$ and extraordinary axis $\hat{e}$ if the medium is anisotropic in the $\hat{x}, \hat{y}$ plane, as defined below. The ray 300 arrives at a boundary 304 between the first medium 302 and a second medium 308. As the ray 300 crosses the boundary 304, it is refracted at an angle Θ_2 that is a function of the index of refraction n_2 of the second medium 308, where again, n_2 depends on the ordinary and extraordinary indices of refraction of the medium, and also depends on the angle the ray 300 makes with the ordinary and extraordinary axes $\hat{o}$ and $\hat{e}$ if the medium is anisotropic in the $\hat{x}, \hat{y}$ plane.
While the angle of refraction is shown as negative, the discussion herein may be related equally to positive refraction in most cases.

The following discussion assumes one of the principal axes of the first medium 302 (defined to be $\hat{z}_1$) is aligned with one of the principal axes of the second medium 308 (defined to be $\hat{z}_2$). A further condition is that this common direction (defined as $\hat{z}_1 = \hat{z}_2 = \hat{z}$) lies in the plane of the interface between the two media 302, 308. A Cartesian basis set ($\hat{x}, \hat{y}, \hat{z}$) can be defined such that $\hat{x}$ is perpendicular to the plane of the boundary 304, and the vectors $\hat{y}$ and $\hat{z}$ are parallel to it. The ordinary axis $\hat{o}$ and extraordinary axis $\hat{e}$ experienced by the ray 300 are also in the $\hat{x}, \hat{y}$ plane. (It is important to note that, although $\hat{o}$ and $\hat{e}$ are used to represent an ordinary and extraordinary axis, this is not meant to imply a uniaxial material; the dielectric constant in the $\hat{z}$ direction can be anything.) For the structure described for this embodiment, light rays that experience positive refraction, negative refraction and/or reflectionless refraction travel in the $\hat{x}, \hat{y}$ plane and are also polarized so that the electric displacement

$\vec{D}$ lies in the $\hat{x},\hat{y}$ plane and the magnetic field $\vec{H}$ lies in the $\hat{z}$ direction. This configuration is structured to allow simplified discussion of refraction confined to the $\hat{x},\hat{y}$ plane.

Note that the indices of refraction n_1, n_2 may be simplifications of the actual index of refraction, because the index of refraction of each medium may depend upon the direction of the wave traveling through the medium. For example, if the first medium 302 is an anisotropic medium, the index of refraction n_1 experienced by a wave traveling through the medium will depend upon an ordinary component n_{1o} and an extraordinary component n_{1e}. Similarly, if the second medium is an anisotropic medium, it may also have ordinary and extraordinary indices n_{2o}, n_{2e}. On the other hand, if the medium is isotropic, the ordinary and extraordinary indices of refraction will be the same.

In a simplified case where the first and second media 302, 308 are the same isotropic material, the index of refraction experienced by a propagating wave will remain constant across the boundary and the wave will propagate un-refracted. Additionally, because the refractive index does not change, no energy will be reflected at the boundary.

In a slightly more complex case, similar to that of the Zhang paper, the first and second media may be the same anisotropic material. It has been shown by Zhang et al., that if certain conditions are met, the amount of energy reflected at the boundary will be zero for identical anisotropic materials, even when the materials are rotated relatively such that the ordinary axis of the first media 302 is inclined at the negative of the angle defined by the ordinary axis of the second media 308. However, because a given polarization component of the wave experiences a change in index of refraction (the lightwave will be refracted.

Unlike the limited application of Zhang et al., the media 302, 308 on either side of the boundary 304 of Figure 3 are not limited to identical, anisotropic media. In a first embodiment according to the invention, the first material 302 is isotropic in the $\hat{x},\hat{y}$ plane, having equal ordinary and extraordinary indices of refraction n_{1o}, n_{1e}. The second

medium 308 is anisotropic in the $\hat{x}, \hat{y}$ plane, having an ordinary index of refraction n_{2o} different from its extraordinary index of refraction n_{2e}.

For the case where the first medium 302 is isotropic in the $\hat{x}, \hat{y}$ plane and the second medium 308 is anisotropic in the $\hat{x}, \hat{y}$ plane, the indices of refraction of the two media 302, 308 are related by their geometric mean according to the relationship:

$$n_1 = \sqrt{n_{2o} \cdot n_{2e}}$$

In this embodiment, the magnetic permeability μ of both media is a) the same in both media, and b) isotropic in both media. Defining the permittivities by,

$$\varepsilon_{1o} \equiv \varepsilon_1, \quad \varepsilon_{1e} \equiv \beta_1 \varepsilon_1, \quad \varepsilon_{2o} \equiv \varepsilon_2, \quad \varepsilon_{2e} \equiv \beta_2 \varepsilon_2$$

then the permittivities (for the case where the first medium 302 is isotropic in the $\hat{x}, \hat{y}$ plane and the second medium 308 is anisotropic in the $\hat{x}, \hat{y}$ plane) are related as,

$$\varepsilon_1 = \sqrt{\beta_2 \varepsilon_2{}^2}$$

This relationship can be derived by satisfying certain boundary conditions and a dispersion relation for zero reflected energy.

The fields in each material must satisfy Maxwell's relations. These lead to standard expressions for the fields and a dispersion relation for the wave vector:

$$\vec{H} = H\hat{z}$$

$$\vec{E} = \frac{kH}{\omega\varepsilon}\left\{\hat{e}\frac{\sin\varphi}{\beta} - \hat{o}\cos\varphi\right\}$$

$$k^2 = \mu\varepsilon\omega^2 \cdot \frac{\beta}{\beta\cos^2\varphi + \sin^2\varphi}$$

Where, for an anisotropic material, the electric field $\vec{E}$ is related to the electric displacement $\vec{D}$ and the dielectric tensor $\varepsilon_{x,y}$ by:

$$\begin{pmatrix} D_x \\ D_y \\ D_z \end{pmatrix} = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}.$$

As represented in Figure 2B, k represents the magnitude of the wave number and φ represents the angle between $\vec{k}$ and the principal axis of the respective material 302 or 308. The Poynting vector $\vec{P}$ is defined in the usual way by,

$\vec{P} = \vec{E} \times \vec{H}$.

For reflectionless refraction to occur, a wave incident on the boundary is completely transmitted from medium 1 to medium 2, and no portion of the wave is reflected back into medium 1. This implies a set of continuity equations at the boundary. Among these are:

$$\begin{aligned} \hat{z} \cdot \vec{H}_1 &= \hat{z} \cdot \vec{H}_2 \\ \hat{y} \cdot \vec{E}_1 &= \hat{y} \cdot \vec{E}_2 \\ \hat{y} \cdot \vec{k}_1 &= \hat{y} \cdot \vec{k}_2 \end{aligned}$$

For the geometry in Figure 2B, these can be written as:

$$\begin{aligned} &\frac{1}{\beta_2 \varepsilon_2}\{\beta_2 \cos\phi_2 d_2 + \sin\phi_2 h_2\} = \frac{1}{\beta_1 \varepsilon_1}\{\beta_1 \cos\phi_1 d_1 + \sin\phi_1 h_1\} \\ &\sin\phi_2 d_2 - \cos\phi_2 h_2 = \sin\phi_1 d_1 - \cos\phi_1 h_1 \end{aligned}$$

using:

$$d_1 \equiv k_1 \cos\varphi_1 \quad , \quad h_1 \equiv k_1 \sin\varphi_1 \quad , \quad d_2 \equiv k_2 \cos\varphi_2 \quad , \quad h_2 \equiv k_2 \sin\varphi_2$$

Satisfying the dispersion relation in each medium produces:

$$\frac{1}{\beta_2\varepsilon_2}\left(\beta_2 d_2^{\ 2} + h_2^{\ 2}\right) = \frac{1}{\beta_1\varepsilon_1}\left(\beta_1 d_1^{\ 2} + h_1^{\ 2}\right).$$

The above equations are satisfied for arbitrary incident angles (in the $\hat{x}, \hat{y}$ plane) under the following conditions:

$$\beta_1\varepsilon_1^{\ 2} = \beta_2\varepsilon_2^{\ 2}$$

$$\sqrt{\beta_1}\cos^2\phi_1 + \frac{1}{\sqrt{\beta_1}}\sin^2\phi_1 = \sqrt{\beta_2}\cos^2\phi_2 + \frac{1}{\sqrt{\beta_2}}\sin^2\phi_2$$

If the first medium 302 is isotropic, then $\beta_1=1$, and the condition that $\beta_1\varepsilon_1^{\ 2} = \beta_2\varepsilon_2^{\ 2}$ reduces to $\varepsilon_1 = \sqrt{\beta_2\varepsilon_2^{\ 2}}$.

While the embodiment described above relates to a ray traveling from an isotropic medium to an anisotropic medium, propagation in the opposite direction (i.e., from an anisotropic medium to an isotropic medium) may also be within the scope of the invention.

In another embodiment, both the first medium 302 and the second medium 308 are anisotropic in the $\hat{x}, \hat{y}$ plane, though they are different media. However, the two media are selected such that the geometric means of their ordinary and extraordinary indices of refraction are substantially equal, as can be represented by:

$$n_{1o}n_{1e} = n_{2o}n_{2e}$$

or, equivalently:

$$\beta_1\varepsilon_1^{\ 2} = \beta_2\varepsilon_2^{\ 2}.$$

The analysis for this is the more general portion of the analysis above, where it is not simplified by assuming the first medium 302 is isotropic.

One skilled in the art will recognize that most naturally occurring media of different material types will not have equal geometric means of their ordinary and extraordinary indices of refraction. In part because the above relationships do not necessarily require that the two media be of the same material, this aspect may be reduced somewhat. For example, the index of refraction of some man-made materials can be controlled to some extent. This ability can be used to more closely satisfy the relationships described above. Moreover, in some materials, the ordinary and/or index of refraction may depend upon the exterior circumstances, such as applied magnetic or electrical fields.

Further, one skilled in the art will recognize that extremely precise control of the index of refraction may be difficult, and that many benefits of the approaches described herein may be realized by substantially complying with the geometric mean relationships of the above equations, rather than exactly satisfying the relationships.

The above approach is not limited to a single boundary between two materials. For example, as shown in Figure 4, a lightwave 400 traveling through a first medium 402 crosses a boundary 404 and enters a second medium 406. The lightwave 400 produces a refracted wave 408 that propagates through the second medium 406 to a boundary 410. At the boundary 410, the refracted wave 408 enters a third medium 412 to produce a second refracted wave 414. At each of the boundaries 404, 410, the amount of energy reflected depends upon the relative indices of refraction on opposite sides of the boundary. At the first boundary 404, the geometric mean of the ordinary and extraordinary indices of refraction n_{1o}, n_{1e} in the first medium 402 equals the geometric mean of the ordinary and extraordinary indices of refraction n_{2o}, n_{2e} in the second medium 406.

Similarly, at the second boundary 410, the geometric mean of the ordinary and extraordinary indices of refraction n_{2o}, n_{2e} in the second medium 406 equals the geometric mean of the ordinary and extraordinary indices of refraction n_{3o}, n_{3e} of the third medium 412.

The above approach may be extended to a larger number of layers, as represented by Figure 5. Once again, the geometric means of the indices of refraction on opposite sides of boundaries 500, 502, 504, 506 are substantially equal. While the layers in Figure 5 are represented as rectangular and having uniform thickness, the approach here is not necessarily so limited. For example, the thickness of the layers may vary from layer to layer. Further, individual layers may have non-uniform thicknesses, as represented by the trio of wedges 602, 604, 606 shown in Figure 6.

In still another approach, presented in Figure 7, a first section of material 702 has an ordinary index of refraction n_{1o} and an extraordinary index of refraction n_{1e}. A second section of material 704 abuts the first material 702 and defines a first interface 708. The second section of material 704 has a gradient index of refraction that begins at a left index of refraction n_{2L} and changes to a right index of refraction n_{2R}. This discussion assumes that the second material is isotropic for clarity of presentation, however, the embodiment is not necessarily so limited. In some applications, it may be desirable for the second material 704 to be a gradient index, anisotropic material. This would likely be achieved with manmade materials.

A third material 706 abuts the second material 704 and defines a second interface 710. The third material 706 has an ordinary index of refraction n_{3o} and an extraordinary index of refraction n_{3e}. In this structure, the second material 704 provides a transitional layer between the first material 702 and the third material 706. For index matching at the first interface, the left index of refraction n_{2L} equals the geometric mean of the first ordinary index of refraction n_{1o} and the first extraordinary index of refraction n_{1e}. Similarly, for index matching at the second interface, the right index of refraction n_{2R} equals the geometric mean of the third ordinary index of refraction n_{3o} and the third extraordinary index of refraction n_{3e}.

While the previous embodiments have been described in the context of a constant set of refractive indices, dynamic adjustment may also be within the scope of the invention. For example, as shown in Figure 8, a first material 800 abuts a second, dynamically controllable material 802. In one embodiment, the dynamically controllable material 802 is an electrooptic material. As is known, electro-optic materials, such as $LiNbO_3$, have indices of refraction that depend upon applied electric fields. As represented by a pair of electrodes 804 and 806 and a voltage source 808, an electric field E may be applied to the second material 802. While the electric field E is presented as being applied transverse to a propagating ray 810, other directional applications may be appropriate depending upon the electro-optic tensor of the particular material.

In another embodiment, the dynamically controllable material 802 may be a polarization rotating material, as represented in the structure of Figure 9. In this structure, the dynamically controllable material 802 provides a transitional layer between a first material 900 and a third material 902. The first material 900 has an ordinary index of refraction n_{1o} and an extraordinary index of refraction n_{3o} whose geometric mean matches that of the ordinary and extraordinary indices of refraction n_{3o}, n_{3e} of the third material 902. However, for proper matching of the materials, it may be desirable that the polarization of light 904 exiting the first material 900 be rotated before entering the third material 902. The dynamically controllable material 802 can rotate a polarization of the light 904, responsive to an applied electric field E, represented by a voltage source V and respective electrodes 910, 908. For example, dynamic control may be used to establish conditions for substantially reflectionless refraction between the dynamically controllable material 802 and the first or second materials 900, 902.

Alternatively, the index of refraction or other material property of the dynamically controllable material 802 may be varied to direct the propagating energy out of plane. It should be noted that the layers of materials described herein are shown with exemplary aspect rations and thicknesses. However, the invention is not so limited. The materials may be made almost arbitrarily thin, on the order of one or a few wavelengths in many

applications, thereby allowing the optical elements and structures described herein to be very thin.

Although the embodiment described above with respect to polarization rotation presumes that the first and third materials have the same geometric mean of their indices of refraction, it may be useful in some applications to have the geometric means be different. One approach to this is to combine the transitional index approach of Figure 7 or the active control approach of Figure 8 to rotate polarization and transition between differing geometric mean index of refractions. Similarly, the approaches of Figures 7 and 8 can be combined to allow active control and transition.

Note that while the dynamically controllable materials of Figures 8 and 9 respond to electric fields, other dynamically controllable materials may be within the scope of the invention. For example, some materials respond to magnetic fields, temperature, optical energy, stress, or a variety of other inputs. Moreover, the dynamically controllable materials may be incorporated into other structures including the structures described earlier with respect to Figures 5 and 6.

In addition to linear stacks of materials, other configurations may be within the scope of the invention. For example, as represented diagrammatically in Figure 10, a series of wedges 1000, 1002, 1004, 1006, 1008, 1010, 1012, may be arranged in a geometric structure, such as a generally circular structure or polygon. While the structure of Figure 10 includes seven wedges for clarity of presentation, the actual number in arrangement of wedges may be larger or smaller depending upon the desired result and the amount of refraction at each interface.

In the structure of Figure 10, the refraction at the interfaces is selected such that a ray 1014 propagating through one of the wedges completes a relatively circular loop. The polygonal structure 1016 thus forms a resonator ring. Optical resonators are useful in a variety of applications, including as resonators for lasers, filters, gyroscopes, or switches as described, for example, in U.S. Patent No. 6,411,752 entitled VERTICALLY

COUPLED OPTICAL RESONATOR DEVICES OVER A CROSS-GRID WAVEGUIDE ARCHITECTURE to Little, et al.; WO0048026A1 entitled OPTICAL WAVEGUIDE WAVELENGTH FILTER WITH RING RESONATOR AND 1xN OPTICAL WAVEGUIDE WAVELENGTH FILTER to Chu, et al., published August 17, 2000; U.S. Patent No. 6,052,495 entitled RESONATOR MODULATORS AND WAVELENGTH ROUTING SWITCHES to Little, et al.; U.S. Patent No. 6,603,113 to Numai entitled GYRO COMPRISING A RING LASER IN WHICH BEAMS OF DIFFERENT OSCILLATION FREQUENCIES COEXIST AND PROPAGATE IN MUTUALLY OPPOSITE CIRCULATION DIRECTIONS, DRIVING METHOD OF GYRO, AND SIGNAL DETECTING METHOD; and in Liu, Shakouri, and Bowers, "Wide Tunable Double Ring Resonator Coupled Lasers," IEEE Photonics Technology Letters, Vol. 14, No. 5, (May 2002) each of which is incorporated herein by reference.

While the embodiments described above focus primarily on optical elements and incorporate optical terminology in many cases, the techniques, structures, and other aspects according to the invention are not so limited. For example, in some applications, it may be desirable to implement structures configured for other portions of the electromagnetic spectrum. For example, as shown in Figure 11, the input energy may be radio frequency (RF). In this structure, a first material 1100 is a manmade structure including periodically positioned RF structures 1102. The first material has dielectric constants ε_{1o}, ε_{1e} corresponding respectively to its ordinary and extraordinary axes. The first material 1100 adjoins a second material 1104 having dielectric constants ε_{2o}, ε_{2e} corresponding respectively to its ordinary and extraordinary axes. Manmade materials having anisotropic sets of dielectric constants are known. For example, as described in (Shelby, Huock), such materials have been shown to operate at around 10 GHz.

In the embodiment of Figure 11, the adjoining materials are such that they satisfy the equation:

$$\beta_1 \varepsilon_1^{\ 2} = \beta_2 \varepsilon_2^{\ 2}$$

$$\sqrt{\beta_1}\cos^2\phi_1 + \frac{1}{\sqrt{\beta_1}}\sin^2\phi_1 = \sqrt{\beta_2}\cos^2\phi_2 + \frac{1}{\sqrt{\beta_2}}\sin^2\phi_2$$

In one embodiment, each of the materials has a respective anisotropic dielectric constant, such that:

$$\varepsilon_{1o} \neq \varepsilon_{1e}$$

and

$$\varepsilon_{20} \neq \varepsilon_{2e}$$

In another embodiment, the first material is isotropic, such that :

$$\varepsilon_{1o} = \varepsilon_{1e}$$

As described with respect to previous embodiments, the electromagnetic wave, though shown propagating in one direction may propagate in the opposite direction and still satisfy the above configuration, for many structures. While the descriptions above have generally referred to specific materials or manmade analogs, in some applications one or more layers of isotropic materials may be air, vacuum, gas, liquid or other substances, including substances having a unity index of refraction. In such cases, the anisotropic material may have an index less than unity. For example, a material having aligned metal fibers in an isotropic dielectric may have an extraordinary index less than 1. The net geometric mean of the material in certain orientations can then equal substantially 1.

While the exemplary embodiments of Figures 1-10 are presented with reference to optical systems and terminology, those skilled in the art will recognize that at least a portion of the devices and/or processes described herein can apply to other types of systems, including RF, X-ray, or other electromagnetic elements, processes, or systems.

The foregoing detailed description has set forth various embodiments of the devices and/or processes via the use of block diagrams, diagrammatic representations, and examples. Insofar as such block diagrams, diagrammatic representations, and examples contain one or more functions and/or operations, it will be understood as notorious by those within the art that each function and/or operation within such block

diagrams, diagrammatic representations, or examples can be implemented, individually and/or collectively, by a wide range of hardware, materials, components, or virtually any combination thereof.

Those skilled in the art will recognize that it is common within the art to describe devices and/or processes in the fashion set forth herein, and thereafter use standard engineering practices to integrate such described devices and/or processes into elements, processes or systems. That is, at least a portion of the devices and/or processes described herein can be integrated into an optical, RF, X-ray, or other electromagnetic elements, processes or systems via a reasonable amount of experimentation.

Those having skill in the art will recognize that a typical optical system generally includes one or more of a system housing or support, and may include a light source, electrical components, alignment features, one or more interaction devices, such as a touch pad or screen, control systems including feedback loops and control motors (e.g., feedback for sensing lens position and/or velocity; control motors for moving/distorting lenses to give desired focuses). Such systems may include image processing systems, image capture systems, photolithographic systems, scanning systems, or other systems employing optical, RF, X-ray or other focusing or refracting elements or processes.

The foregoing described embodiments depict different components contained within, or connected with, different other components. It is to be understood that such depicted architectures are merely exemplary, and that in fact many other architectures can be implemented which achieve the same functionality. In a conceptual sense, any arrangement of components to achieve the same functionality is effectively "associated" such that the desired functionality is achieved. Hence, any two components herein combined to achieve a particular functionality can be seen as "associated with" each other such that the desired functionality is achieved, irrespective of architectures or intermedial components. Likewise, any two components so associated can also be viewed as being "operably connected" or "operably coupled" to each other to achieve the desired

functionality.

While particular embodiments of the present invention have been shown and described, it will be understood by those skilled in the art that, based upon the teachings herein, changes and modifications may be made without departing from this invention and its broader aspects and, therefore, the appended claims are to encompass within their scope all such changes and modifications as are within the true spirit and scope of this invention. Furthermore, it is to be understood that the invention is solely defined by the appended claims. It will be understood by those within the art that, in general, terms used herein, and especially in the appended claims (e.g., bodies of the appended claims) are generally intended as "open" terms (e.g., the term "including" should be interpreted as "including but not limited to," the term "having" should be interpreted as "having at least," the term "includes" should be interpreted as "includes but is not limited to," "comprise" and variations thereof, such as, "comprises" and "comprising" are to be construed in an open, inclusive sense, that is as "including, but not limited to," etc.). It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases "at least one" and "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to inventions containing only one such recitation, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an" (e.g., "a" and/or "an" should typically be interpreted to mean "at least one" or "one or more"); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation is explicitly recited, those skilled in the art will recognize that such recitation should typically be interpreted to mean at least the recited number (e.g., the bare recitation of "two recitations," without other modifiers, typically means at least two recitations, or two or more recitations).